Lidar Measurements of Aerosol Scattering in the Troposphere and Stratosphere

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ABSTRACT

A two-color Rayleigh/Raman lidar has been developed to study the properties of the middle and lower atmosphere. The LAMP (Lidar Atmospheric Measurements Program) lidar profiler was placed in service at Penn State University during the summer of 1991. The LAMP lidar uses two wavelengths, 532 and 355 nm, in the transmitted beam and up to eight detectors in the receiver. The instrument is arranged in a monostatic configuration, which permits useful measurements in the near field, as well as in the far field. The detector system uses a mechanical shutter to block the high intensity low altitude signal from the high altitude detectors until the beam has reached an altitude of 20 km. The Nd:YAG laser includes a doubling crystal and a mixing crystal to produce a 532 and a 355 nm beam. The low altitude backscatter signals of the visible and ultraviolet beams are detected as analog signals and digitized at 10 MSps to provide 15 meter resolution from the surface to 25 km. The high altitude signals, obtained by photon counting techniques, are separated into 500 nanosecond range bins to provide 75 meter resolution, from 20 to 80 km. The detector also contains two first Stokes vibrational Raman channels to measure the N_2 signal at 607 nm and the H_2O signal at 660 nm. Measurements of the rotational Raman backscatter provides the possibility to obtain temperature profiles in the presence of clouds and in the boundary layer.

The results reveal the continuous presence of a relatively small aerosol particles through the troposphere. These particle sizes are comparable to the wavelength of the light and exhibit a signal, in the vicinity of 5 km, which is typically greater than the molecular backscatter by a factor of 2 at the 532 nm wavelength and by a factor of 10 at the 355 nm wavelength. The small aerosol component of the tropospheric backscatter was found to be relatively uniform as a function of latitude over the ocean, from Arctic (70°N) to Antarctic (65°S). In the presence of clouds, the variation in the background small aerosol was remarkably small. The cloud presence does not significantly change the slope or magnitude of the small aerosol component near the cloud layer except for the expected attenuation by the cloud. The magnitude of the ultraviolet extinction due to this small aerosol component is quite significant. The influence of the turbidity due to small aerosol scattering has been investigated to prepare these results for a study of the turbidity contribution to the radiative transfer in the atmosphere.

EXPERIMENT BACKGROUND

Results from the ARL/PSU LAMP (Lidar Atmospheric Measurements Program) lidar instrument have been examined to determine the aerosol component of the lower atmosphere. The instrument has been used since mid-1991 to measure the properties of the atmosphere and is based upon developments of two previous instruments (Philbrick, 1991). The two-color lidar approach is most useful in examining and separating the molecular, aerosol and cloud scattering components. Most of the results have been obtained at the PSU campus but a most significant data set was obtained during the LADIMAS campaign. The LAtitudinal DIstribution of Middle Atmosphere Structure (LADIMAS) experiment (Philbrick, et al, 1992) has provided a unique set of measurements which are improving our understanding of the atmosphere. The project included ship-board and rocket range coordinated measurements between 70N to 65S to study the structure, dynamics and chemistry of the atmosphere. Results on dynamical processes, such as gravity waves, tidal components, as well as, the formation of the layers of meteoric ion and neutral species, have been obtained with lidar, digisonde, microwave radiometer, and spectrometers. The cooperative study of the atmosphere was undertaken by researchers from several laboratories, including Penn State University, University Bonn, University Wuppertal, Lowell University, and others. Several of the parameters studied have never been measured before over such a wide range of latitudes. Instruments were assembled aboard the German research vessel RV POLARSTERN while this vessel was sailing from the Arctic to the Antarctic seas between October 8, 1991 and January 2, 1992. This paper examines the lower atmosphere portion of the results and summarizes some of the major conclusions about the atmospheric turbidity, caused by aerosols, from the results of the LAMP lidar.

The global distribution of atmospheric turbidity is an important property to examine, along with the global distribution of clouds, to determine the radiation budget at the Earth. An increase in green-house gasses and their warming effect, could be countered by the decrease in the transmission of the Earth's atmosphere and the increased albedo effects due to an increase in turbidity and cloudiness. Since both of these effects are nonlinear processes and their coupling is uncertain, it is very important to better understand the turbidity distribution and changes.

The importance of turbidity in describing the color of the sky (Nichols, 1908) has been recognized since the realization that the blue sky was due to molecular scattering (Rayleigh, 1899). The turbidity of the atmosphere is defined as the ratio of the total attenuation (due to both aerosols and molecules) to the attenuation that would be due only to the molecules (van de Hulst, 1980). Typical values of the turbidity vary between about 2 and 6 on clear days. The total lidar backscatter signal divided by the expected signal for molecular backscatter forms a ratio which is similar to the turbidity definition. It will not be the same because the attenuation is not directly related to the backscatter intensity. We have examined the backscatter intensity, and the extinction obtained from the N_2 Raman signal and from inversion calculations (see companion paper, Maruvada, et al, 1993). It is, nevertheless, useful to examine the lidar backscatter ratio to study the variation in turbidity.

MEASUREMENTS

The initial data of LADIMAS, for the LAMP lidar instrument, were gathered at Andoya Rocket Range, Norway. On the leg between Tromso, Norway, and Bremerhaven, Germany, the operational testing of the instrument on the ship was completed. Measurements were made on each clear night, and on some occasions, the measurements were made below and into the clouds. The measurements included high and low altitude channels for the 532 and 355 nm wavelengths, Raman shifted N_2 at 607 nm, Raman shifted H_2O at 660 nm, and 532 nm measurements from a second telescope simultaneously recorded.

An example of the LAMP lidar measurements is shown in Figure 1. The signals from the low and high altitude channels of the 532 and 355 nm and the N_2 Raman channel at 607 nm and the water vapor Raman at 660 nm are shown as $1/R^2$ corrected profiles. The low and high altitude signal channels have been merged together to obtain continuous profiles from near the surface to altitudes between 60 and 80 km. The profiles of nitrogen and water vapor are also shown. The 532 and 355 nm profiles have been tied to model profile from the USSA 1976 model at 40 km. The model profile attachment, at 40 km, is in a region of pure molecular scattering. These profiles represent the pure molecular profile, without accounting for either aerosol and molecular extinction or the enhanced backscatter due to aerosols.

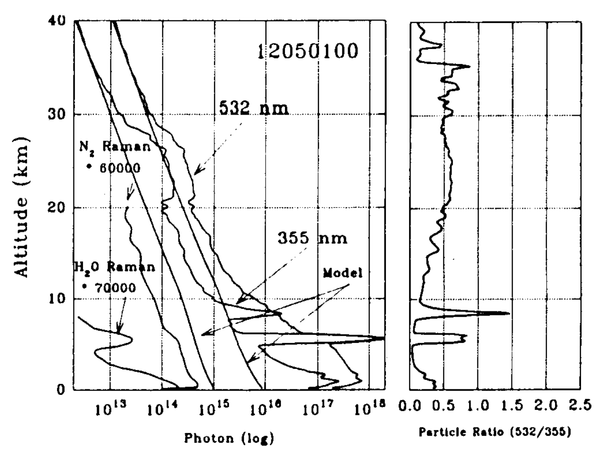

Figure 1. The raw data signals, corrected for R^2, from the low and high altitude channels are shown together with reference profiles of molecular scattering only for 5 December 1991 on the POLARSTERN near 40°S latitude. The boundary layer (below 3 km) clouds at 6 and 9 km, and the stratospheric aerosol layer centered about 25 km are easy to distinguish.

The backscatter ratio plots shown in Figure 2 are for the same data run as the profiles of Figure 1. Examination of Figures 1 and 2 shows that the presence of the cloud layers does not significantly change the background profile of the small aerosols that are distributed throughout the troposphere. This point is most easily seen by comparing the profiles with those of Figure 3. The Profiles of Figure 3 were obtained one day before, on 4 December 1991, when no clouds were present. The background aerosol backscatter profiles for the two days are

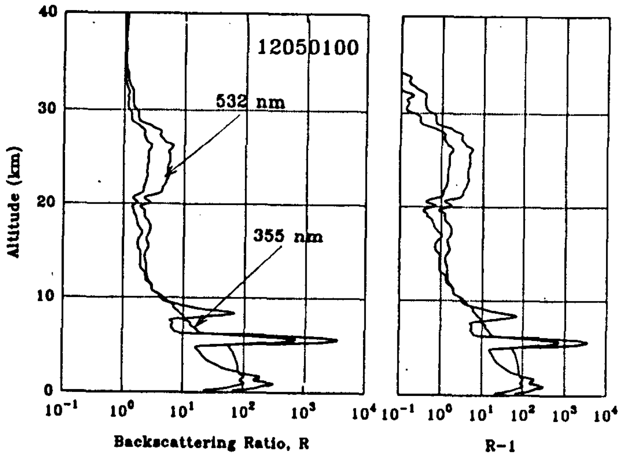

Figure 2. The backscatter ratio for the profiles of 5 December 1991, shown the Figure 1, show the aerosol backscatter intensity relative to the molecular atmosphere.

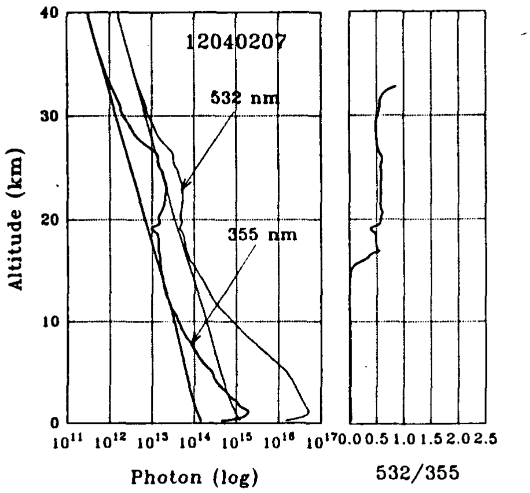

Figure 3. The backscatter ratio profiles for 4 December 1991, the day prior to that in Figures 1 and 2, when no cloud layers were present.

nearly identical, appearing to differ only by the extinction losses in the clouds. All of the profiles obtained on the POLARSTERN showed similar profiles for the aerosol distribution through the troposphere. The indication is that the troposphere above the marine boundary layer may be relatively stable. There was always a strong backscatter through the troposphere, like that of Figure 3, in all of the profiles from the ship. The results of Figures 4 and 5, results from PSU, show a typical profiles for the continental aerosols.

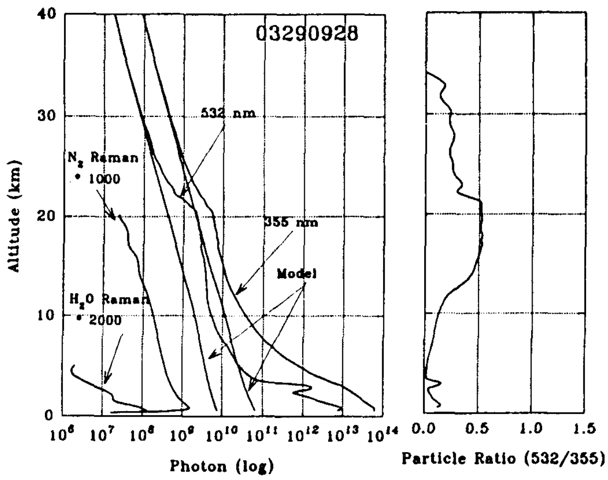

Figure 4. Lidar profiles obtained at PSU on 29 March 1992, which show the backscatter from the continental aerosol.

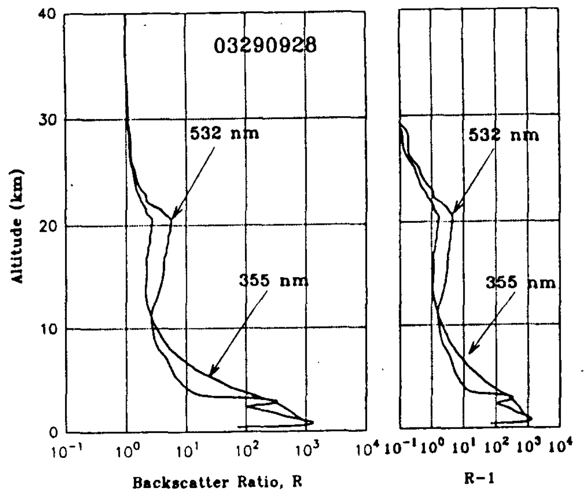

Figure 5. Backscatter profiles for the data shown in Figure 4, for continental aerosols.

Figure 6 shows the extinction coefficient as a function of spherical particle size for the 532 and 355 wavelengths. It is interesting to note the variation as a function of wavelength compared to the variations observed in the backscatter intensity at the two wavelengths.

CONCLUSIONS

The two-color lidar is proving to be a valuable tool in studies of the study of the distribution of aerosols in the lower atmosphere. The stratospheric aerosol layer generally shows a larger backscatter ratio for the 532/355 relative to the molecular scattering ratio, indicating that the particles are approximately the same size as the wavelength. That is

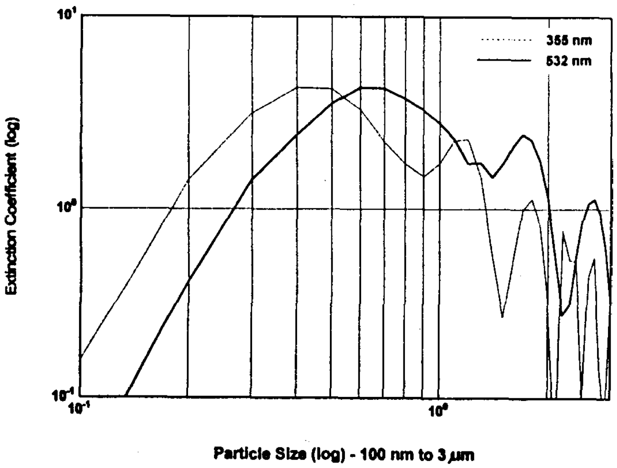

Figure 6. Particle scattering extinction as a function of particle size in the range between 100 nm and 3 microns for the 532 and 355 nm laser wavelengths.

the region where spherical particles, which is probably not the case, would have about twice the extinction probability as a 355 nm. The small tropospheric aerosols show a very strong scattering at 355 relative to the 532, which could happen when the size is small compared to the wavelength, but is also possible that the particle size is near the one micron. In clouds, the 532 backscatter is stronger than the 355 nm, which is in agreement with scattering for a large range of sizes larger than about 1.5 microns. The results which have been obtained are being prepared for an analysis of the general characteristics of aerosol scattering effects on turbidity which impact on radiation transfer in the atmosphere.

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REFERENCES

Carswell, A.I., "Lidar Remote Sensing of Atmospheric Aerosols," SPIE Vol. 1312, 206-220, 1990.

van de Hulst, H. C., *Multiple Light Scattering*, Academic Press, 1980.

Nichols, E. L. "Theories of the Color of the Sky" *Proc. Am. Phys. Soc.* XXVI, p 497, 1908.

Philbrick, C. R., "Lidar Profiles of Atmospheric Structure Properties," Earth and Atmospheric Remote Sensing, SPIE Vol. 1492, 76-84, 1991.

Philbrick, C. R., D. B. Lysak, T. D. Stevens, P. A. T. Haris and Y.-C. Rau, "Atmospheric Measurements Using the LAMP Lidar during the LADIMAS Campaign," 16th ILRC, NASA Conf. Pub. 3158, p 651-654, 1992.

Rayleigh, Lord, "On the Transmission of Light Through an Atmosphere Containing Small Particles in Suspension, and on the Origin of the Blue of the Sky," Philosophical Magazine, XLVII, p 375, 1899.